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G. Roati, M. Zaccanti, C. d'Errico, Jacopo Catani, Michele Modugno, Andrea Simoni, M. Inguscio, Massimo Inguscio

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G. Roati,[1] M. Zaccanti,[1] C. D'Errico,[1] J. Catani,[1] M. Modugno,[2] A. Simoni,[3] M. Inguscio,[1] and G. Modugno[1]

[1]*LENS and Dipartimento di Fisica, Università di Firenze, INFN and CNR-INFM, 50019 Sesto Fiorentino, Italy*

[2]*LENS and Dipartimento di Matematica Applicata, Università di Firenze, INFN, and BEC-INFM Center, Università di Trento, I-38050 Povo, Italy*

[3]*Laboratoire de Physique des Atomes, Lasers, Molécules et Surfaces, Unités Mixtes de Recherche 6627 du CNRS and Université de Rennes, 35042 Rennes Cedex, France*

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We produce a Bose-Einstein condensate of ^{39}K atoms. Condensation of this species with a naturally small and negative scattering length is achieved by a combination of sympathetic cooling with ^{87}Rb and direct evaporation, exploiting the magnetic tuning of both inter- and intraspecies interactions at Feshbach resonances. We explore the tunability of the self-interactions by studying the expansion and the stability of the condensate. We find that a ^{39}K condensate is interesting for future experiments requiring a weakly-interacting Bose gas.

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Two-body interactions play a major role in the production and in the properties of Bose-Einstein condensates (BECs) made of ultracold atoms [1]. Atomic species with naturally large repulsive interactions such as ^{87}Rb [2] or ^{23}Na [3] have collision properties favorable for the preparation process. However, there is growing interest in studying Bose-Einstein condensates where the interactions can be precisely tuned, magnetic Feshbach resonances [4,5] being a key tool in this respect. One of the main motivations is the formation of an almost ideal condensate, i.e., one with vanishing interatomic interactions. The availability of such a system is essential for studying phenomena where even a weak interaction can hide the underlying physics of interest. A noticeable example is in the field of disordered systems, where experiments performed with ideal quantum gases can shed new light on the interdisciplinary phenomenon of Anderson localization [6,7]. An ideal BEC would also be the most appropriate source for matter-wave interferometry, combining maximal brightness with the absence of collisional decoherence [8]. The possibility of dynamically tuning the interactions in a BEC could also open new directions towards Heisenberg-limited interferometry [9].

Feshbach resonances have been observed in most of the atomic species that have been condensed so far: ^{23}Na [5], ^{85}Rb [10], ^{133}Cs [11,12], ^{7}Li [13], ^{87}Rb [14], ^{52}Cr [15]. Magnetic tuning of the interactions to small values around zero can be performed in lithium, a possibility already exploited to realize bright solitons in a weakly attractive BEC [13]. Cesium also presents an experimentally accessible region of nearly vanishing scattering lengths at which the small internal energy of a weakly-interacting cesium BEC has been investigated [12].

In this Letter, we report Bose-Einstein condensation of a new atomic species ^{39}K. The combination of broad Feshbach resonances and a small background scattering length $a_K \simeq -33\, a_0$ [16] makes this system very promising for the study of weakly-interacting condensates. Direct evaporative cooling of this species had been prevented by unfavorable zero-field collisional properties [17,18]. Sympathetic cooling with ^{87}Rb has recently been proven to work for ^{39}K [18] as efficiently as for the other potassium isotopes [19,20], but condensation was still prevented by the negative value of a_K. We now bring ^{39}K to quantum degeneracy by a combination of sympathetic cooling with ^{87}Rb and direct evaporative cooling, exploiting the resonant tuning of both inter- and intraspecies interactions at Feshbach resonances. Presence of one broad homonuclear Feshbach resonance allows us to tune a_K in the condensate from large positive to small negative values. The possibility of precisely adjusting a_K around zero is demonstrated by studying the condensate expansion and its stability.

The experimental techniques we use are similar to the ones we developed for the other potassium isotopes [18–21]. We start by preparing a mixture of ^{39}K and ^{87}Rb atoms in a magneto-optical trap. The mixture contains about 10^9 Rb atoms at $T \simeq 100\ \mu$K and 10^7 K atoms at $T \simeq 300\ \mu$K. We simultaneously load the two species in a magnetic potential in their stretched Zeeman states $|F = 2, m_F = 2\rangle$, and then we perform a selective evaporation of rubidium on the hyperfine transition at 6.834 GHz (the hyperfine splitting of ^{39}K is 462 MHz). Potassium atoms are efficiently sympathetically cooled via interspecies collision [18], in spite of the small scattering length $a_{KRb} \simeq 28\ a_0$ [21]. With this technique, we are able to prepare after 25 s of evaporation samples containing typically 10^6 Rb atoms and 2×10^5 K atoms [22] at $T = 800$ nK.

Further cooling of the mixture in the magnetic potential would in principle be possible. However, condensation would be accompanied by collapse [23] because of the negative scattering length of ^{39}K at low magnetic fields. We therefore exploit the possibility of tuning a_K to positive values by performing the last part of evaporation in an optical potential in the presence of a homogeneous mag-

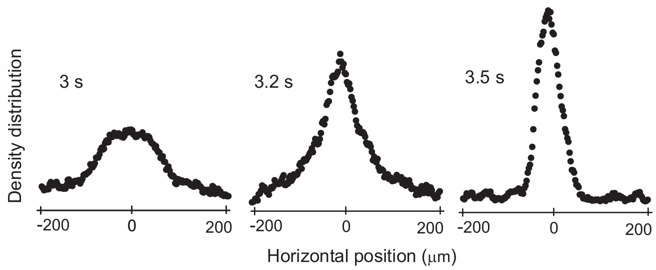

FIG. 1. Phase transition to a ^{39}K BEC. The three profiles are taken at different times during the final stage of forced evaporation in the optical trap (see Fig. 2). The profiles are obtained by vertically integrating the column density measured after release from the trap and 15 ms of ballistic expansion.

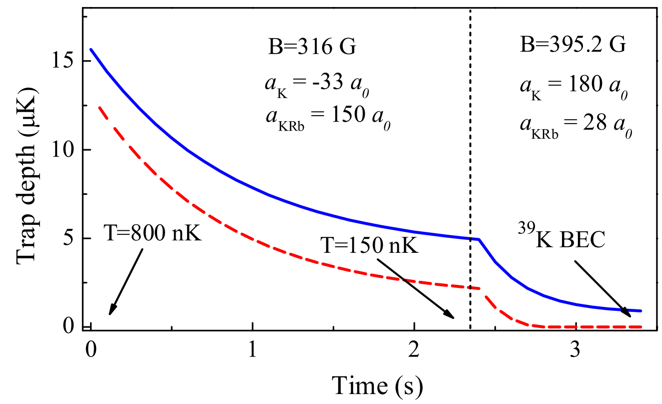

FIG. 2 (color online). Sketch of the relevant parameters of the system during the evaporation in the optical potentials. The trap depth for K (solid line) is always larger than the one for Rb (dashed line). The two exponential ramps for K have time constants of 0.9 and 0.45 s, respectively.

netic field. We have indeed discovered several broad Feshbach resonances for this potassium isotope [24,25], a very favorable one being in the ground state $|1, 1\rangle$ at about 400 G. We have also performed a detailed analysis of several such resonances in order to construct a quantum collisional model able to accurately predict the magnetic-field dependence of a_K [24]. We will make use of this analysis throughout this Letter.

The K-Rb mixture is adiabatically transferred to an optical trap created with two focused laser beams at a wavelength $\lambda = 1030$ nm, with beam waists of about 100 μm and crossing in the horizontal plane. The two species are then transferred to their absolute ground states $|1, 1\rangle$ via adiabatic rapid passage, and further cooled by reducing the power in the laser beams by means of acousto-optic modulators. The optical trap is designed in such a way as to evaporate mainly Rb by exploiting the increased gravitational sag of this heavier element. We find that cooling of ^{39}K can be greatly enhanced by increasing a_{KRb} at one of the interspecies Feshbach resonances that exist in this mixture [21]. At a first stage lasting 2.5 s, a homogeneous magnetic field is thus tuned near a 8.5 G-wide interspecies Feshbach resonance centered at 317.9 G [26]. We find that sympathetic cooling is optimized at a field of 316 G, where $a_{KRb} \simeq 150\ a_0$. At this magnetic field, the homonuclear ^{39}K cross-section is still small, $a_K \simeq -33\ a_0$.

When both gases are close to quantum degeneracy ($T \simeq$ 150 nK), we make a_K positive and large by shifting the magnetic field in proximity to a 52 G-wide ^{39}K resonance, centered at 402.4 G, and we continue the evaporation for 1 s. Because of the different trap depths for the two species, Rb is soon completely evaporated and further cooling of K relies only on intraspecies collisions. We find for this phase an optimal scattering length $a_K \simeq 180\ a_0$ obtained for $B =$ 395.2 G. At this field, the two species are only weakly coupled, since $a_{KRb} \simeq 28\ a_0$. Figure 1 shows the phase transition of the K cloud to a Bose-Einstein condensate, detected via absorption imaging after a ballistic expansion. The critical temperature we measure is about 100 nK, and our purest condensates typically contain 3×10^4 atoms. The frequencies of the optical trap at the end of the evaporation are $\omega = 2\pi \times (65, 74, 92)$ s^{-1} in the (x, y, z) directions, respectively. The whole evaporation procedure in the optical trap is summarized in Fig. 2.

Once the condensate is produced, a_K can be further tuned. We have explored the magnetic-field region below the homonuclear Feshbach resonance in which the condensate is stable. The experiment starts with a pure BEC created at $B_0 = 395.2$ G. The field is then adiabatically brought to a final value B in 30 ms. After 5 ms, the optical trap is switched off, and the cloud expands for 31.5 ms before absorption imaging is performed with a resonant beam propagating along the y direction. The magnetic field is switched off just 5 ms before imaging, to ensure that a_K does not change during the relevant phases of the expansion. Examples of absorption images are shown in Fig. 3. The measured atom number and the mean width $\sigma = (\langle x^2\rangle + \langle z^2\rangle)^{1/2}$ are shown in Fig. 4, together with the magnetic-field dependence of a_K as calculated using our quantum collision model [24].

Between 350.2 G and 350.0 G, we observe a sudden drop of the atom number that can be attributed to a collapse [23] of the BEC for too negative a_K. In this regime, the sample is no more in equilibrium, and the presence of strong excitations is evident (see leftmost panels in Fig. 3). On

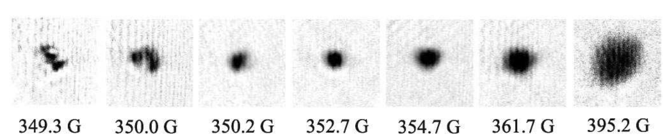

FIG. 3. Sample images of a ^{39}K condensate at various magnetic fields in the vicinity of the 52 G-wide Feshbach resonance centered at 402.4 G, taken after 31.5 ms of expansion. The size shrinks as the scattering length a_K is decreased, and the condensate eventually collapses for negative a_K. The field of view is $300 \times 300\ \mu$m.

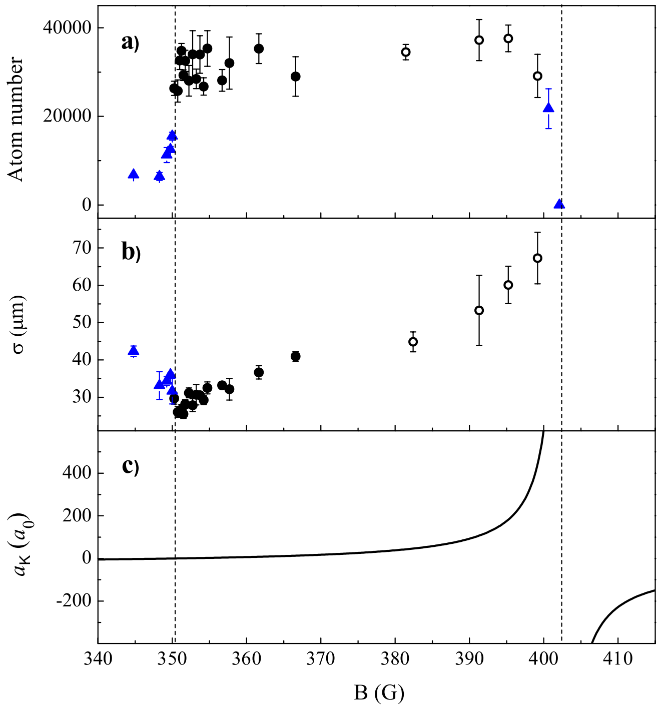

FIG. 4 (color online). Tuning the interaction in a ^{39}K condensate. (a) atom number; (b) width of the cloud after 31.5 ms of ballistic expansion; (c) theory prediction for the scattering length. The two dashed lines indicate the expected position of the zero-crossing and resonance center. Condensates are either fitted with a Thomas-Fermi profile (circles) in the region of large interactions or a Gaussian profile (dots) in the region of weak interactions. Atom number and width of uncondensed clouds are directly extracted from the raw images (triangles). Each data point is the average of at least three measurements.

the other extreme, the field can be brought in proximity of the resonance center. Here, we observe that the BEC is depleted by three-body recombination, whose rate scales as a_K^4 [27] close to a Feshbach resonance. For example, the lifetime of the BEC in the optical trap, which is typically around 3 s, is shortened to about 200 ms when the field is set to 399.2 G, where $a_K = 440$ (40) G.

The width of the condensate after the expansion shown in Fig. 4(b) features a decrease by almost a factor of 3 as the field strength shifts from the resonance to the zero-crossing region. This is due to the variation of the interaction strength in the condensate. At the long expansion time of this experiment, $\sigma \propto \sqrt{E_{\rm rel}}$, where $E_{\rm rel}$ is the release energy of the condensate. The latter quantity is expected to decrease as $a_K^{2/5}$ in the Thomas-Fermi limit, i.e., for large positive a_K. Its value equals the kinetic energy of the harmonic oscillator ground state for $a_K = 0$ and becomes even smaller for $a_K < 0$. The sharp increase of the width below 350.2 G reported in Fig. 4 reflects the presence of excitations in the collapsed system.

To gain insight into the observed phenomenology, we have compared the condensate widths with numerical calculations based on the Gross-Pitaevskii theory [28]. In Fig. 5, we plot σ as a function of a_K; here, the abscissa values for the experimental data have been calculated using the theoretical $a_K(B)$ [24]. The horizontal error bar is dominated by the uncertainty in the model for $a_K(B)$, which amounts to about 0.27 a_0 in the zero-crossing region. The decrease in σ with decreasing a_K is the result of two general effects: (i) reduction of the condensate width in the trap; (ii) reduction of the interaction energy released during the first phases of the expansion. Note in Fig. 5(a) the good agreement between theory and experiment in the broad range of values of a_K in which the condensate is stable. The slow decrease of σ for moderately large and positive a_K is followed by a faster decrease in the region of the zero-crossing.

In Fig. 5(b), we compare theory and experiment on a much smaller region around the zero-crossing, including also the experimental data points corresponding to a collapsed cloud. The hatched region indicates the critical scattering length for collapse $a_c = -0.57(20)\ a_0$ predicted by the theory for the nominal atom number we had in this experiment, $N = 3.5 \times 10^4$. The width of the cloud keeps on decreasing as a_K becomes negative and increases again at collapse. In this experiment, collapse is apparently hap-

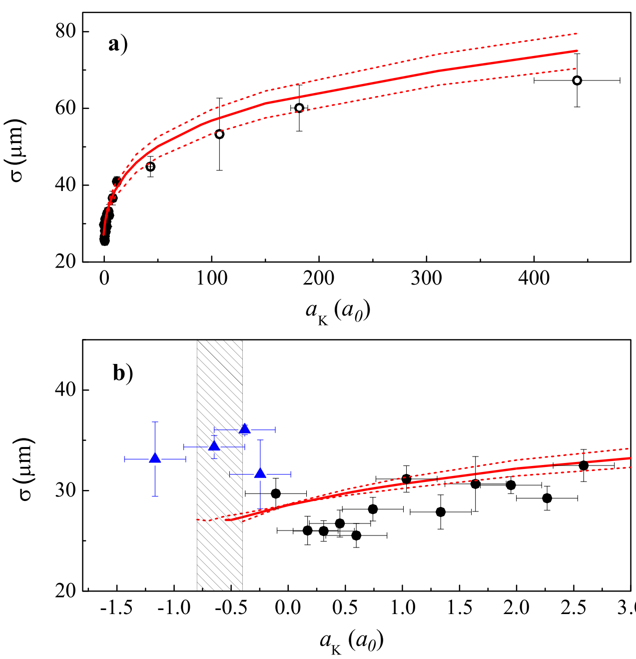

FIG. 5 (color online). (a) Scattering-length dependence of measured (dots) and calculated (lines) mean width σ. The two dashed lines indicate the range of variation of σ due to a 30% systematic uncertainty on atom numbers. (b) Zoom into the zero-crossing region. Both condensed samples (dots) and collapsed samples (triangles) are shown. The horizontal error bars are determined by the uncertainty on $a_K(B)$. The hatched region indicates the critical a_K for collapse as predicted by the numerical calculation, including its variation due to the uncertainty in the atom number.

pening at a slightly subcritical scattering length $a_K = -0.2(3)\ a_0$. This might be due to a loss of adiabaticity of our magnetic-field ramp in this region of negative a_K. Although the ramp duration is much longer than the trap period, it might still excite the monopole collective mode of the condensate which has a vanishing frequency for a_K approaching a_c [29].

In conclusion, we have produced a Bose-Einstein condensate of ^{39}K atoms in which the scattering length can be precisely tuned over a large range and adjusted around zero. This atomic species is particularly advantageous in producing a weakly-interacting condensate, since it combines a broad Feshbach resonance with a small background scattering length. For this resonance, the theoretical model [24] predicts a sensitivity $da_K/dB \simeq 0.55\ a_0/\mathrm{G}$ around 350 G. Therefore, a magnetic-field stability of the order of 0.1 G will in principle allow us to tune the scattering length to zero to better than 0.1 a_0 in future experiments. This degree of control appears superior to that achievable in most other species which present either narrower resonances and/or larger background scattering lengths, the only exception being ^{7}Li [13].

A weakly-interacting ^{39}K Bose gas may have a variety of applications, ranging from Anderson localization of matter waves to high-sensitivity atom interferometry. We note that the in-trap size of a weakly-interacting condensate is comparable to that of the ground state of the trapping potential, that is $\sqrt{\hbar/m\bar{\omega}} = 1.84\ \mu\mathrm{m}$ in the present experiment. Such small size opens interesting perspectives for inertial measurements with high spatial resolution [30].

We expect that a binary ^{39}K-^{87}Rb BEC can also be efficiently produced, thus widening the possibilities offered by potassium-rubidium mixtures. Such a binary condensate could be used for various applications and is especially appealing for the production of ultracold heteronuclear molecules.

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